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Bardsey – an island in a strong tidal stream

Underestimating coastal tides due to unresolved topography

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Abstract

Bardsey Island is located at the western end of the Llŷn Peninsula in north-west Wales Separated from the mainland by a channel some 3 km wide, it is surrounded by reversing tidal streams of up to 4 ms^{-1} at spring tides. These local hydrodynamic details and their consequences are unresolved by satellite altimetry, nor are they represented in regional tidal models. Here we look at the effects of the island in the strong tidal stream in terms of the formation and shedding of eddies, and the budgets for tidal energy dissipation. We show, using local observation and a satellite altimetry constrained product, that the island has a large impact on the tidal stream, and that even the latest altimetry database seriously under-represents the tidal stream due to the island not being resolved. The effect of the island leads to an underestimate of the current speed in the altimetry data in the channel of up to a factor of three, depending on tidal state, and the average tidal energy resource is underestimated by a factor 6. The observed tidal amplitudes are higher at the mainland than at the island, and there is a detectable phase lag in the tide across the island – this effect is not seen in the altimetry data. The underestimate of the tide in the altimetry data has consequences for tidal dissipation and wake effect computation and show that local observations are key to correctly estimate tidal energetics around small-scale coastal topography.

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1 Introduction

Scientific understanding of global tidal dynamics is well established. Following the advent of satellite observations, several tidal constituents can be mapped from altimetry data, and the products constrained using in situ tidal databases (e.g., TPXO - Egbert and Erofeeva, 2002 and http://volkov.oce.orst.edu/tides/tpxo9_atlas.html, and FES - https://www.aviso.altimetry.fr /en/data/products/auxiliary-products/global-tide-fes.html). There is, however, still an issue in terms of spatial resolution of the altimetry products: even the most recent tidal models have only 1/30° resolution (equivalent to ~3.2 km in longitude at the equator, some 1.9 km in the domain here, and 3.2 km in latitude everywhere). This means that smaller topographic features and islands are unresolved, and may be "invisible" to the altimetry product even if the features may be resolved in the latest bathymetry databases, e.g., GEBCO (https://www.gebco.net/). Consequently, local tidal dynamics, for example wake effects behind an island or headland, are poorly represented. Here, we use a series of tide-gauge measurements from Bardsey Island in the Irish Sea (Figure 1) to evaluate the effect of the island on the tidal dynamics as they track around Bardsey Island and the Llŷn peninsula in North Wales, UK.

Bardsey Island, which we use for this study, is a rocky melange of sedimentary and igneous rocks including some granites, located 3.1 km off the Llŷn Peninsula in North Wales (Figure 1a). It is approximately 1 km wide, though only 300 m at the narrowest part, and 1.6 km long. It reaches 167 m at its highest point. Bardsey Sound, between the Llŷn peninsula and the island, experiences strong tidal currents. The relatively small scale of the island and the separating Sound means that the local detail is not "seen" in the altimetry products: this will lead to effects induced by the island being missed in the altimetry data. The uncaptured (by TPXO) very active local tidal dynamics allows us to compare altimetry constrained tidal characteristics, especially amplitudes, for the region with accurate local observations, and quantify the validity limits of the altimetry products. We will do a direct comparison of tidal amplitudes around the island (see Figure 1b for TG locations and a summary of the in-situ tides). We also consider whether, and when, in the tidal cycle, flow separation occurs in the wake of the island.

We will use some basic fluid-flow parameters. Transition to turbulence can be parameterised in terms of the Reynolds number, Re, defined as $Re = UD/\nu$, where U is a velocity scale, D is the size of the object, and $\nu \sim 100$ is the kinematic viscosity (Edwards et al., 2004; Wolanski et al., 1984). It indicates when the transition to turbulence occurs: at low Reynolds numbers, Re<1, the flow is quite symmetric upstream and downstream, and there is no flow separation at the object. As the Reynolds number is increased to the range 10 < Re <40, laminar separation happens and results in two steady vortices downstream. As Re increases further, up to Re<1000, these steady vortices are replaced by a periodic von Karman vortex street, whereas if Re>1000, the separated flow is fully turbulent.

Another useful non-dimensional number for this type of investigation is the Strouhal number, $St = fD/U$. Here, f is the frequency of the shedding of vortices, and fully developed vortices are generated when T>f and T is the frequency of the oscillating flow (Dong et al., 2007; Magaldi et al., 2008). If, on the other hand, the tidal frequency is larger than f only one wake eddy will be shed on each tidal cycle, if it has time to form at all.

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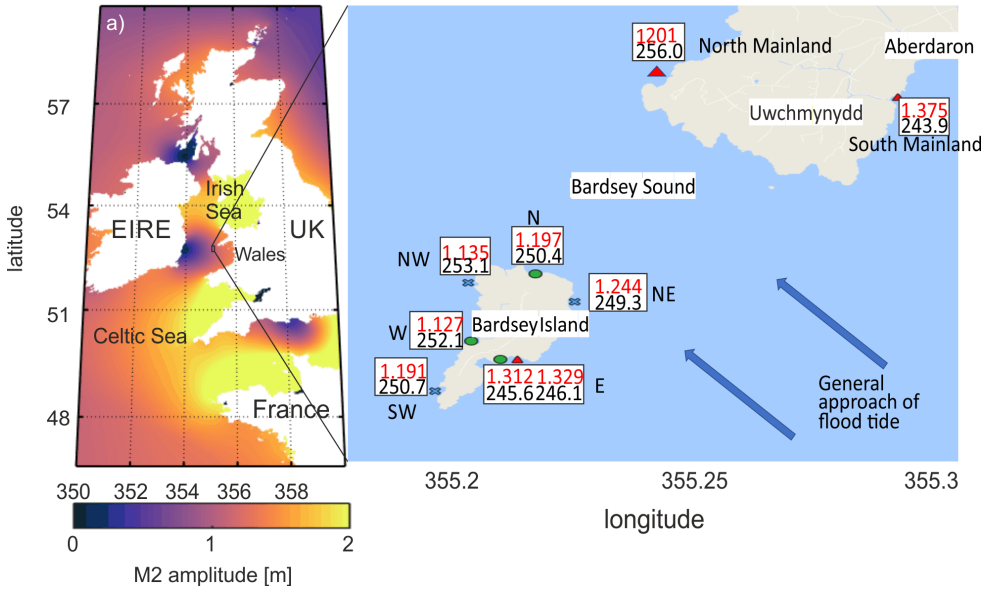

Figure 1: a) Map of the European shelf showing M_2 tidal amplitudes in meters, from TPXO9. b) details of local topography and tidal characteristics in the vicinity of Bardsey Island. The symbols mark the TG location, with green ellipses les denoting phase 1, blue crosses phase 2, and red triangles phase 3. Note that East was occupied twice, during Phases 1 and 3. The red numbers in the text boxes are the amplitudes (in meters) and the phases (in degrees, one degree is two minutes in time) from the harmonic analysis for each tide gauge. Map data ©Google Earth.

2 Observations

2.1 In situ data collection

The tidal elevations around Bardsey were measured in three phases, from summer 2017 through to spring 2018 (Table 1 and Figure 1b). Note that site East, the main Harbour for the island, Y Cafn, was occupied twice as a control, during Phase 1 and 3, and that all the other instrument deployments were bottom mounted a few tens of metres offshore in depths between 3.2 to 16.5 m. The instruments used were RBR pressure recorders with a measurement resolution better than 0.001 m. The instruments were set to sample every 6 minutes, and the resulting pressure series were subjected to harmonic analysis using the NOC TASK software (details are available from https://www.psmsl.org/train_and_info/software/task2k.php).

Analyses were made for 26 constituents, including Mean Sea Level and eight related constituents, appropriate for a month or more of data (see, e. g., Pugh and Woodworth, 2014). The non-tidal residuals have standard deviations appropriate for the region at the times of year of the deployments. Phase 2 residuals, however, are noticeably higher than the other two phases because it included one of the most severe storms and waves in local memory: hurricane Ophelia. A good indication of the

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quality of the in-situ observations and analyses is given by the consistency in the tidal ages and S_2/M_2 amplitude ratios in the final column of Table 2.

Table 1: Details of the pressure gauge deployments. Amplitudes are given to three decimal places as appropriate for the uncertainties, whereas the timing of constituent phases is probably better than 0.5 degrees (1 minutes for M_2).

Station	Latitude	Longitude	Deployed	Recovered	Depth mean (m)	Non-tidal Standard deviation (m)
Phase 1						
North	52.767	355.213	1605 25/5/17	1400 11/7/17	3.9	0.113
East	52.756	355.207	1557 25/5/17	1350 3/7/17	7.0	0.141
West	52.753	355.202	1045 27/5/17	1128 5/7/17	5.6	0.116
Phase 2						
Northwest	52.765	355.203	0000/ 1/9/17	1110 27/10/17	6.7	0.156
Southwest	52.748	355.197	0000/ 1/9/17	1145 30/10/17	7.5	0.154
Northeast	52.762	355.220	0000/ 1/9/17	1240 30/10/17	5.5	0.150
Phase 3						
East	52.753	355.207	1512 7/09/18	0912 05/10/18	3.2	0.095
South Mainland	52.759	355.275	1348 7/09/18	1024 06/10/18	4.8	0.088
North Mainland	52.781	355.236	1500 7/09/18	1512 10/10/18	16.5	0.083

2.2 Altimetry data

The altimetry data came from the TPXO9 ATLAS (http://volkov.oce.orst.edu/tides/tpxo9_atlas.html; (Egbert and Erofeeva, 2002). The resolution is 1/30° in both latitude and longitude (3.7 km and 2.2 km at Bardsey). We used the elevation and transport information, and their respective phases, for the M_2, S_2, N_2, and M_4 constituents. In the following calculations, we define "astronomical" as the largest possible current speed or amplitude, computed as the sum of the amplitudes with the four tidal constituents we discuss. This is thus a limited form of Highest and Lowest Astronomical Tide.

2.3 LANDSAT data

Landsat-8 data images were used to identify possible eddies in the currents. Data were downloaded from the Earth Explorer website (https://earthexplorer.usgs.gov/). True colour enhanced RGB images were created with SNAP 7.0 using the panchromatic band for red (500 - 680nm, 15m resolution), band 3 for green (530 - 590nm, 30m resolution) and Band 2 for blue (450 - 510 nm, 30m resolution). The blue and green bands were interpolated using a bicubic projection to the 15m panchromatic resolution, and brightness was enhanced to allow easier visualization of the wakes. Images were taken between 11:00 and 12:00 UTC over the area.

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3 Results

Table 2 Summary of harmonic tidal analyses. TPXO9 data interpolated to the TG location, which are given in **BOLD**. "H" is amplitude (in m) and "G" is phase (degrees relative to Greenwich, given in italics to ease reading). TGX09 amplitudes are given to 0.01 m, whereas the *in situ* precision justifies resolution to 0.001 m.

		M2		**S2**		**M4**		**Tidal Age (hours)**	**M2/S2 ratio**
		TG	**TPXO**	**TG**	**TPXO**	**TG**	**TPXO**		
PHASE 1									
North	H	**1.197**	1.17	**0.458**	0.45	**0.112**	0.12		**0.383**
	G	***250.4***	*254.4*	***287.1***	*287.3*	***20.5***	*32.4*	**36.7**	
East	H	**1.312**	1.16	**0.514**	0.42	**0.144**	0.12		**0.392**
	G	***245.6***	*253.8*	***283.4***	*286.7*	***45.8***	*34.3*	**37.8**	
West	H	**1.127**	1.15	**0.434**	0.42	**0.136**	0.12		**0.385**
	G	***252.1***	*253.7*	***288.4***	*286.6*	***34.9***	*34.8*	**36.3**	
PHASE 2									
NW	H	**1.135**	1.16	**0.431**	0.4215	**0.130**	0.12		**0.380**
	G	***253.1***	*254.7*	***287.1***	*287.6*	***35.0***	*33.4*	**34.0**	
SW	H	**1.191**	1.15	**0.461**	0.42	**0.088**	0.12		**0.387**
	G	***250.7***	*253.4*	***285.5***	*286.3*	***26.0***	*35.6*	**34.8**	
NE	H	**1.244**	1.5	**0.482**	0.43	**0.094**	0.12		**0.387**
	G	***249.3***	*253.8*	***284.0***	*286.7*	***42.6***	*32.8*	**34.7**	
PHASE 3									
East	H	**1.329**	1.16	**0.522**	0.42	**0.136**	0.12		**0.393**
	G	***246.1***	*253.8*	***282.8***	*286.7*	***53.2***	*34.3*	**36.7**	
S. Mainland	H	**1.375**	1.21	**0.538**	0.44	**0.149**	0.14		**0.391**
	G	***243.9***	*251.5*	***280.7***	*284.4*	***49.9***	*37.1*	**36.8**	
N. Mainland	H	**1.201**	1.20	**0.461**	0.43	**0.072**	0.12		**0.384**
	G	***256.0***	*254.6*	***290.4***	*287.6*	***39.0***	*29.1*	**34.4**	

3.1 Amplitudes and phases

A spring-neap cycle of parts of the data from the East and West gauges in phase 1 is plotted in Figure 2. The TG data show amplitudes of 1.197 m (North), 1.312 m (east) and 1.127 m (west). These give across-island difference in amplitude of about -14% (on spring tides a level difference across 300 m of up to 0.3 m), and an along-island difference of about -9% (compared to the data from the Eastern TG). There is also 6.5° (13 minutes) phase difference for M_2 across the island between the east and the west, with the east leading, consistent with the tide approaching the island from the south and east and then swinging up around the Llŷn Peninsula headland (see Figures 2b,c and 3). This curvature of the streamlines as the flow is squeezed through Bardsey Sound and swings up around the peninsula, leads to the enhanced generation of non-linear higher tidal harmonics due to curvature on the

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reversing tidal stream curves. This contributes to the large M_4 amplitudes around the island and headland (Table 2).

In contrast, the TPXO9 M2 data, which has no island representation, if interpolated linearly to the TG positions, come out as 1.17, 1.16, and 1.15 m for the phase 1 locations (Table 2). The corresponding TPXO-phases are 254.4°, 253.8°, and 253.7°, indicating that there is only a small variation in the tidal signal (2cm in amplitude and 0.7° in phase) over the location of the island in the altimetry data. The results in Table 2 show that there is a substantial effect of the island and limited resolution, inducing a 13% change in amplitude between the TPXO and TG data at station East. These results are supported by the phase 2 measurements (Table 2). Phase 3 saw an extended and different approach to the data collection. We revisited East, but also deployed two gauges on the Llŷn peninsula, on the approach to the island (South Mainland)), and north of it (North Mainland). At South Mainland, TPXO is again underestimating the tidal amplitude by more than 10%. At North Mainland, some 5 km north of Bardsey, and just north of the Sound, however, the TG and TPXO amplitudes are within 1 cm of each other. This again shows the effect Bardsey and local topography, have on the tidal amplitudes in the region.

For the shallow-water tidal harmonics, the TPXO M4 amplitude agrees well with the TG data at North (0.12 and 0.11 m, respectively), but overestimates the amplitude at North Mainland (0.07 m in the TG data and 0.12 m from TPXO; see Table 2). Because higher harmonics are generated locally by the tidal flow itself, this again shows the effect of the island on the tidal stream; the M4 amplitude is halved along Bardsey Sound in the TG data, whereas TPXO overestimates it and shows only minor variability. The overestimate in TPXO can lead to the tidal energetics being biased high in the region if they are based on the altimetry alone.

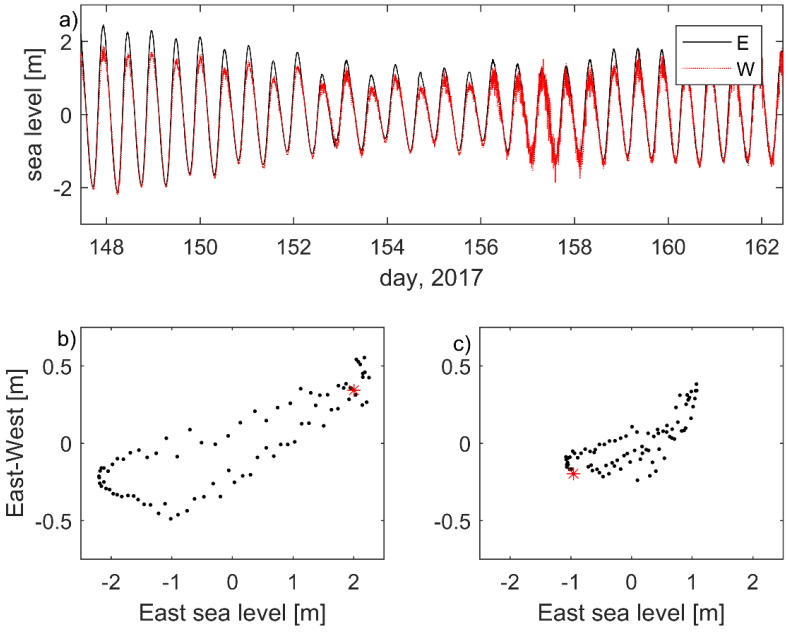

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Figure 2: a: Part of the East (black) and West (red) data series from Phase 1, covering one spring-neap cycle (arbitrary datums).
b and c: plots of the elevation at East vs. the East-West difference in elevation for springs (b, day 147) and neaps (c, day 154). The red stars show the first data point of the day. The progression is clockwise.

3.2 Currents

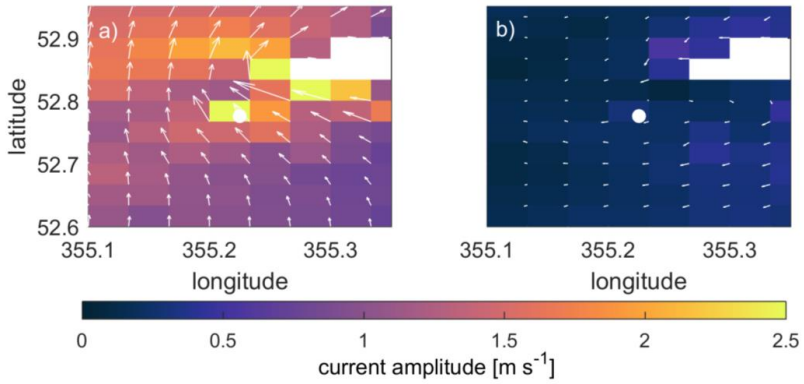

Figure 3: The current magnitude (colour) and vectors at neap ebb (a) and spring flood (b) from TPXO9. The white circle shows the location of Bardsey – note that it is not resolved in the TPXO data base and has been added for visual purposes only.

We do not have access to any current measurements from the region, but the tidal stream is known to reach up to 4 m s^{-1} in the Sound (Colin Evans, pers. comm. and Admiralty chart no. 1971). The TPXO9 spring flood and neap flood currents are shown in Figure 3. It is reasonable to assume that, to first order, the acceleration into the Sound can be described as a frictionless Bernoulli flow driven by the sea-surface elevation change between South and north Mainland (e.g., Stigebrandt, 1980),

$$0.5u^2 = g\Delta H \quad (1),$$

where u is the speed in the Sound, and ΔH is the associated drop in sea-surface elevation (the water column depth changes little between South Mainland and North Mainland and the depth difference is thus neglected). We can add the speed at South mainland, u_{SM}, to Eq. (1) to get the total speed in the strait. Using data for M2 from TPXO9 gives a 0.01 m change in tidal amplitude along the Sound, which when used in Eq. (1) gives a current speed, induced by the sea-level difference, of 0.4 m s^{-1} between South Mainland and North Mainland. If we add the TPXO9 M_2 speed at South Mainland, u_{SM} = 1 m s^{-1} , to this we get u_{M2}=1.4 m s^{-1} at North Mainland from TPXO9. The actual TPXO9 speed at the position of the North Mainland TG is u_{M2} = 1.3 m s^{-1}, and the calculation implies that TPXO underestimates the currents in the Sound. The same computation from the astronomic tide differences gives u_{astro} = 2.7 m s^{-1}, using ΔH=0.07m and $u_{astro,\ SM}$= 1.5 ms^{-1}, which is a serious underestimate compared to the suggested astronomic tide of 4 m s^{-1}. However, the phases are ignored here, and the instantaneous gradient along the sound is larger – for M2 the phase difference equates

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to 13 minutes, so the instantaneous gradient can be up to 11% larger and the resulting flow can thus be up to 23% stronger, or 1.7 m s^{-1}.

If, on the other hand, we take the TPXO speed at South Mainland as true, because it is not as influenced by the presence of the island as North Mainland, and repeat the calculations using the observed changes in amplitudes from the TG data, the 0.16 m drop between South Mainland and North Mainland in the M_2 tidal amplitudes gives 2.8 m s^{-1} in the Sound from M2 alone (or 3.4 m s^{-1} if we include a correction for the phase). The astronomic difference (e.g., using all constituents) between South and North Mainland is 33 cm, giving 2.5 m s^{-1} from the TG difference, which when added to the South Mainland $u_{astro,SM}$ = 1.5 m s^{-1}, gives 4 m s^{-1} at North Mainland – in agreement with the estimates of local sea-going experts, and the Admiralty chart for the Sound.

3.3 Dissipation

In the computations above we neglected friction, which is probably a crude approximation. To first order, dissipation can be computed from the (adjusted) TPXO velocities and from the observed amplitude drop along the Sound by comparing the tidal energy flux, E_f, between the two locations. A decrease in the energy flux between two locations can be associated with local dissipation of tidal energy as the wave propagates them (see e.g., Green et al., 2008). The flux of tidal energy is given by (e.g., Phillips, 1977)

$$E_f = 0.5 c_g \rho g H^2 \quad (3),$$

where H is again the tidal amplitude and $c_g = \sqrt{gh}$ is the speed of the tidal wave (h is the water depth). The dissipation, ε, is then the difference in energy flux between the two mainland TG locations, or $\varepsilon = c_g \rho g (H_{SM}^2 - H_{NM}^2)$, taking c_g constant because h changes little between the TG locations. Using the TG amplitudes, the astronomic tide would then dissipate 243 kW m^{-1}. Over the 3.1 km width of the Sound, this integrates to about 750 MW. The M2 tide contributes 26% of this, or 201 MW. This is approximately 0.1% of the total M_2 dissipation on the European shelf estimated from large-scale altimetry (Egbert and Ray, 2000), and is a reasonable estimate for such an energetic region. Note that this method is independent of the phases between the locations, nor does it depend on the phases between the amplitudes and currents.

If these calculations are repeated using the TPXO elevations, the astronomic dissipation comes out as 126 MW and the M_2 dissipation as 11 MW. This is a substantial underestimate (factors of almost 6 and more than 18, for the astronomic and M_2 tides, respectively), which again highlights the importance of resolving small-scale topography in local tidal energy estimates, and the use of direct observations in coastal areas to constrain any modelling effort. This dissipation occurs only a small fraction of the European Shelf and coastline, and although the Bardsey tides are unusually energetic, underestimated local coastal energy dissipation may be substantial in satellite altimetry data and numerical models.

3.4 Caveat Emptor!

We have shown above that the tidal elevations are underestimated in the altimetry data, and that the current magnitude is most likely underestimated as well, so our computations below are conservative.

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The two extremes in tidal current magnitude in Bardsey Sound can be taken to be the neap tide speed from TPXO9 and the astronomic speed computed using TG data and TPXO combined. We thus have 0.9 m s^{-1} (neaps from TPXO9, not discussed above) as the lower range, and 4 m s^{-1} (astronomic computed) as the upper estimate.

Even using the much-underestimated current speeds from the TPXO-data, the indications are that there would be no stratification locally. The Simpson-Hunter parameter, $X = h/u^3 \approx 70$ for Bardsey Sound (Simpson and Hunter, 1974). This means that the area is vertically mixed due to the tides alone. The eddies shed from the island will add more energy to this, further breaking down any potential stratification from freshwater additions (the Simpson-Hunter parameter is based on heat fluxes only) and act to redistribute sediment. The associated Reynolds number for the Island, $Re=UD/\nu$, then comes out at approximately 10 for the neap flow, or approximately 40 for the astronomic tidal current (using D=1000 m as the width and ν=100 m^2 s^{-1} as the eddy viscosity). This implies laminar separation into two steady vortices downstream of the Island at peak flows, and the vortices can be expected to appear on both ebb and flood flows (Edwards et al., 2004; Wolanski et al., 1984). There may not be any vortex shedding during neap flows, however, because Re~10.

The Strouhal number St = fL/U, is typically about 0.2 for the Re numbers found here (Wolanski et al., 1984), giving $f=St\ U/L = 0.2U/1500 \Rightarrow 1x10^{-4} < f < 5x10^{-4}$ and an associated vortex shedding period of 3-17 hours (L=1500m is the length of the island). This means that fully developed eddies, generated at the higher flow rates, because our tidal period (12.4 hours) is longer than the vortex shedding period (semi-diurnal vs. a few hours), whereas at neap flows, there is no time to develop a fully separated vortex in a tidal cycle.

Figure 4: Landsat 8 images from October 5, 2017 (a) and September 13, 2018 (b) from Landsat 8. The tidal phase are halfway between neaps and springs in a) and just after spring high tide in b). The white dot north of the island in Figure 3b is an exposed rock generating a second wake. See https://landsat.gsfc.nasa.gov/data/ for data availability.

This conclusion is supported by satellite images from Landsat 8 (Figure 4), which shows a very different picture between neaps (Figure 3a) and springs (Figure 4b). At spring tides, there are two clear wakes

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behind the tips of the island (marked with arrows), whereas at neaps (Figure 4a) there is only a more diffuse image in Bardsey Sound, and no signal of a wake behind the south tip of the island.

4 Discussion

This brief account was triggered by an interest in detailed mapping of tides in a reversing tidal stream. The results highlight the effect small coastal islands can have on tides in energetic settings, and they highlight the limitations of altimetry-constrained databases near coastlines where the bathymetry is unresolved. Even though TPXO9, which is used here, is constrained by a series of tide gauges in the Irish Sea, including north and south of Bardsey, the island is some 60 km from the nearest long-term tide gauge (in Holyhead, some 45 km to the north of Bardsey). Consequently, the tidal amplitudes in the database are not representative of the observed amplitudes near the island, and the currents are underestimated by a factor close to 1.5 for the astronomic tide. This underestimate also means that wake effects may be underestimated if one relies solely on altimetry (or coarse resolution numerical models) unable to resolve islands, with consequences for navigation, renewable energy installations, and sediment dynamics.

The results do have wider Implications for, among others, the renewable industry, because we show that local observations are necessary in regions of complex geometry to ensure the energy resource is determined accurately. Using only TPXO data, the dissipation – an indicator of the renewable resource – is underestimating the astronomic potential with a factor 6 of the real resource. There is also the possibility that wake effects behind the island would be neglected without proper surveys, leading to an erroneous energy estimate. The results also highlight that concurrent sea-level and current measurements are needed to fully explore the dynamics and quantify, e.g., further pressure effects of the island on the tidal stream. Consequently, we argue that in any near-coastal investigation of detailed tidal dynamics, the coastal topography must be explicitly resolved, and any modelling effort should be constrained to fit local observations of the tidal dynamics.

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Code/Data availability: The data is available from the Open Science Framework (https://osf.io/kvgur/?view_only=ff2d8bd12a61493aa1dfa9011ecdde81)

Author contributions: JAMG wrote the manuscript and did the computations. DTP did the measurements, processed the TG data, and assisted with the writing.

Competing interests: The authors declare no competing interest

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